Three-channel inter-comparison and direct comparison on-orbit stability analyses as applied to the CERES instruments on the Terra and Aqua satellites

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ABSTRACT

Clouds and the Earth's Radiant Energy System (CERES) is an investigation into the role of clouds and radiation in the Earth's climate system. Four CERES scanning thermistor bolometer instruments are currently operational. Flight model 1 (FM1) and 2 (FM2) are aboard the Earth Observing System (EOS) Terra satellite and FM3 and FM4 are aboard the EOS Aqua satellite. Terra was launched in December 1999 and Aqua in May 2002. Each CERES instrument measures in three broadband radiometric regions: the shortwave (0.3 – 5.0 μm), total (0.3 – >100 μm), and window (8 – 12 μm). Several vicarious analyses have been developed to aid in monitoring the health and stability of the instruments' radiometric measurements. One analysis is a three-channel inter-comparison of the radiometric channel measurements for each instrument. A second analysis compares temporally synchronized nadir measurements for each sensor of two instruments on the same platform. These analyses along with onboard calibrations have been used to monitor the drifts in the shortwave measurements and have provided information used to remove the drift using ground software. Previously documented, these analyses will be reviewed and further results for the Terra CERES instruments will be presented along with initial findings for the CERES instruments on Aqua.

Key Words: CERES, Terra, Aqua, shortwave radiance, stability, nadir footprints

1. INTRODUCTION

The long-term goal of the CERES project is to obtain understanding of the role of clouds in the radiation budget of planet Earth.[1] Currently five CERES instruments are on three satellite platforms in Earth orbit. The CERES prototype flight model (PFM) instrument is aboard the Tropical Rainfall Measuring Mission (TRMM) satellite launched in November 1997.[2] Two CERES instruments, flight model 1 (FM1) and 2 (FM2) are aboard the EOS Terra satellite launched in December 1999. And flight model 3 (FM3) and 4 (FM4) are on the EOS Aqua satellite launched in May 2002. A voltage regulator failed on PFM after the instrument provided eight months of radiance measurements and PFM is no longer operational. Analyses discussed here are restricted to the radiance measurements by the CERES instruments on the Terra and Aqua satellites.

Each CERES scanning thermistor bolometer instrument measures in three broadband radiometric regions: the shortwave (0.3 – 5.0 μm), total (0.3 – >100 μm), and window (8 – 12 μm). Each sensor measures filtered radiance. Filtered radiance is the radiance absorbed by the sensor and has not been adjusted for optical effects of the sensor assembly.[2] The filtered radiance is converted to unfiltered radiance with ground software using the spectral response function associated with each sensor.[3] The spectral response function is dependent on the spectral reflectance, spectral absorptance, and spectral transmission of each sensor. The unfiltered radiance is the radiance incident to the instrument aperture. Once in flight, the sensors' calibration is monitored regularly using known sources. A tungsten lamp is used as a constant source for the shortwave sensor and blackbodies are used as constant sources for the window and total detectors.[2] In addition to the on-orbit calibrations on the instruments, algorithms using ground software have been developed which can indicate stability of instrument measurements. Use of these algorithms has shown that there has been a drift in the ground-calibrated characteristics of the sensors. Further, this drift is occurring in the shortwave region of the measurements. Two analyses have been implemented that identified this drift, a three-channel inter-comparison of the three radiometric

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channels per each instrument and a direct comparison of temporally synchronized nadir measurements between each sensor of the two instruments on the same platform.

The three-channel inter-comparison has shown that either the shortwave sensor or the shortwave portion of the total channel sensor has drifted from its ground-calibrated characteristics for both instruments on the Terra satellite. The direct comparison shows that the two shortwave sensors compare between FM1 and FM2. Further, in-flight calibrations indicate that the shortwave sensors for these instruments are not drifting. These analyses along with ground and on-orbit calibrations were used to isolate the drift as occurring in the shortwave region. Similar analyses applied to the CERES instruments on Aqua indicate a drift in the shortwave sensor measurements of both instruments. This paper will outline the analyses, present further investigation into the shortwave drift problem, and demonstrate methods for correction using ground software.

2. ANALYSES

2.1 Three-Channel Inter-comparison Using Deep Convective Clouds

The three-channel inter-comparison is done on the measured radiance of nadir views of Deep Convective Clouds (DCC) for the three sensors on each instrument. A theoretical basis for the three-channel inter-comparison, can be found in Priestley, et al.[2] DCC are identified using the window sensor radiance equivalent to brightness temperatures less than 215 Kelvin. Multiple nadir footprints occurring in succession meeting the "cold" (215 K) brightness temperature criteria are grouped as a DCC. At least two footprints are required for DCC. Radiances, fluxes, and geolocation of the footprints comprising a DCC are averaged over all the footprints yielding one radiance, flux, and geolocation per DCC. Further, sampling is restricted to between 35 degrees north and south latitude and less than 60 degrees solar zenith with respect to the footprint. The standard deviation of the window radiance was calculated for each group of footprints comprising a DCC. Most standard deviations were less than 10 percent of the window radiance average. Some standard deviations reached on the order of 25 percent of the window radiance average. However, no DCC points were discarded due to large standard deviations of the window radiance.

Using nighttime averaged radiances of each DCC, a correlation between the nighttime window filtered radiance and nighttime longwave unfiltered radiance is derived. This relationship is nearly linear for these "cold" footprints. Figure 1 illustrates the linear relationship between the nighttime filtered window radiance and the nighttime unfiltered longwave radiance for March 2000 measured by the FM1 instrument. The regression coefficient for a linear relationship is 0.957 and the variance is 0.216 $(\text{watt/m}^2/\text{sr})^2$ which are typical values for all months processed.

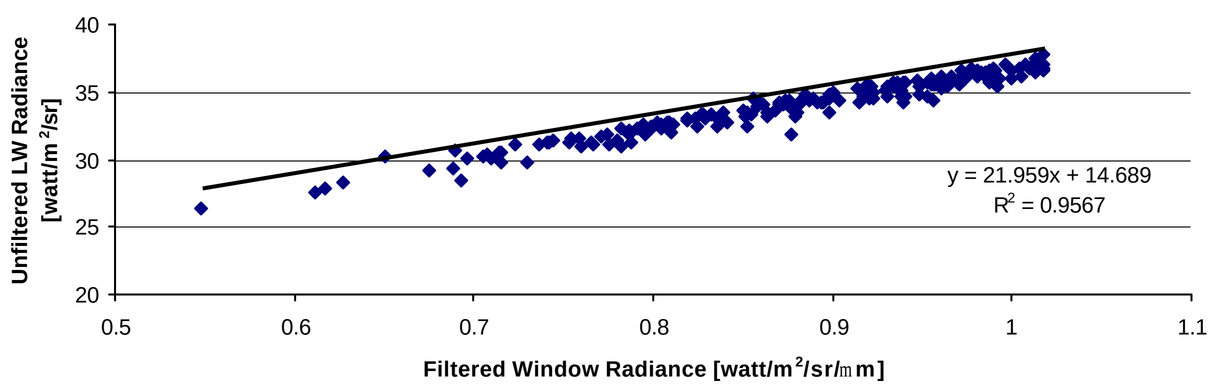


Figure 1: Correlation between filtered window radiance and unfiltered longwave radiance for nighttime DCC in March 2000 detected by FM1.

The resulting regression coefficients are used to generate a derived daytime unfiltered longwave radiance using the window channel. The difference between the measured and derived daytime unfiltered longwave radiance is linearly correlated to the filtered shortwave measurement with a forced zero intercept. A trend plot of the slope of the correlation between the filtered shortwave and the delta longwave over the life of the Terra and Aqua missions is shown in figure 2.

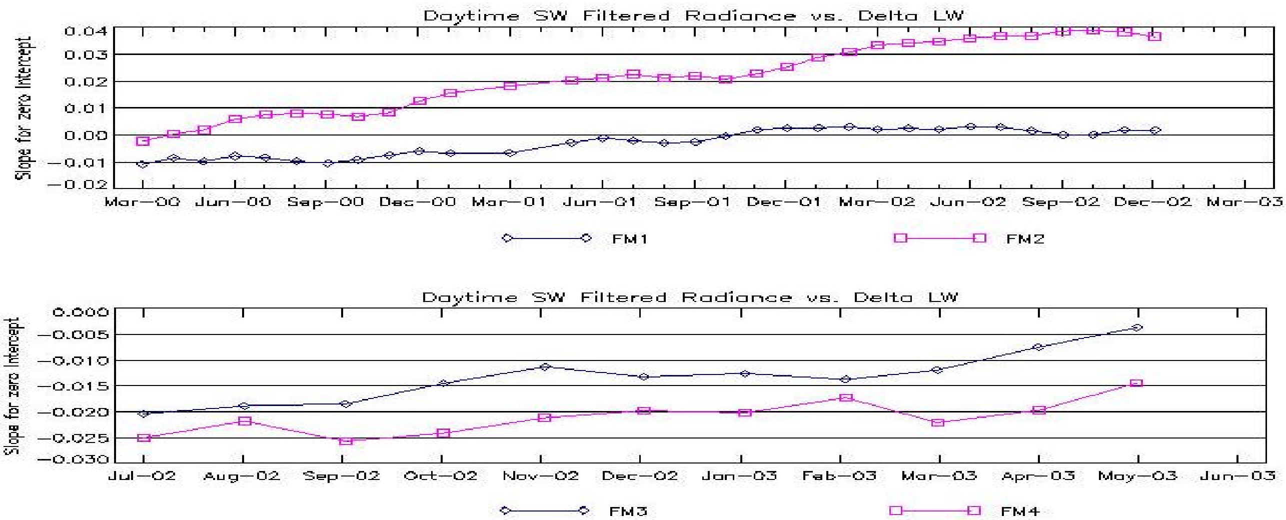


Figure 2: Trending of the ratio of the delta longwave to the measured shortwave channel using the three-channel inter-comparison for BDS and ES-8 Edition 1 data products.

The daytime correlations are quite noisy with the variance often greater than 50 percent of the delta longwave and low correlation coefficients. However, the shortwave and delta longwave should not correlate especially since delta longwave should tend to zero. This still serves as a good trending analysis since nonzero results may indicate a problem. Nighttime correlations are stable in time between filtered window radiance and unfiltered longwave radiance over mission life for both platforms.[4]

2.2 Direct Comparison

The CERES instruments scan from the limb of the Earth on one side of the instrument to the Earth's limb on the opposite side of the instrument and return. One scan takes 6.6 seconds. Each instrument has two nadir footprints, zero viewing zenith angle with respect to the footprint, per scan. The direct comparison analysis pairs the two nadir views of each instrument that are within 1.65 seconds of each other, one quarter of the scan period. These coincident nadir measurements of the two instruments are differenced (FM2 - FM1) for Terra, and (FM4-FM3) for Aqua, and averaged per month based on scene type. All logic used in this analysis, such as scene type and cloudiness, is based on what was detected by the FM1 instrument for Terra and FM3 for Aqua.

2.2.1 Direct Comparison – Terra, Edition 1 Data Products

The trending of the daytime longwave flux differences between the CERES instruments on Terra using Edition 1 data (ES-8) is shown in figure 3 for various scene types. The trending of the nighttime longwave flux direct comparison is shown in figure 4 and daytime shortwave flux trending is plotted in figure 5.

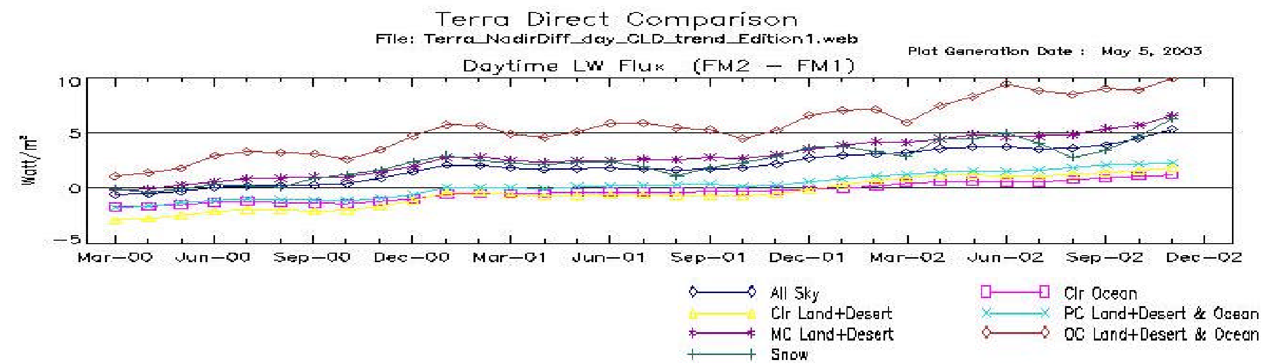


Figure 3: FM2-FM1, Edition 1 data, difference for daytime longwave flux over mission life for all sky conditions and various cloud and surface types.

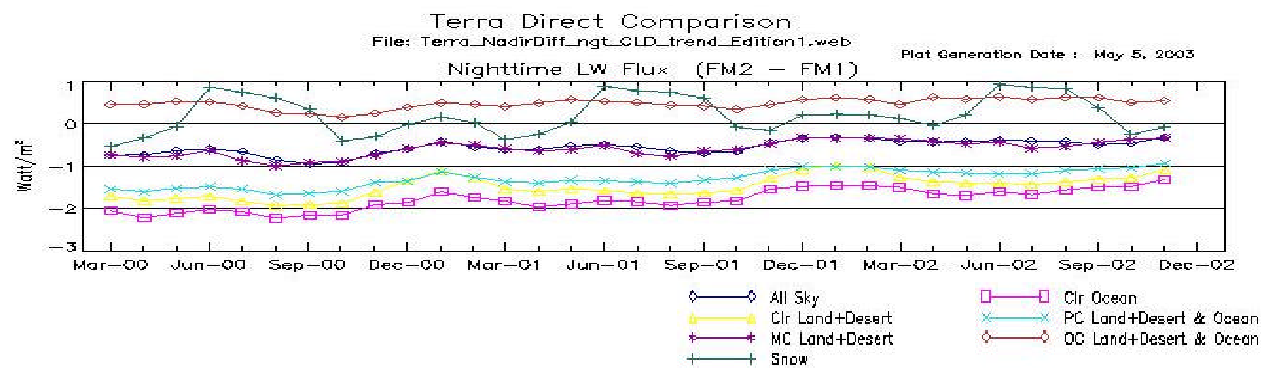


Figure 4: FM2-FM1, Edition 1 data, difference for nighttime longwave flux over mission life for all sky conditions and various cloud and surface types.

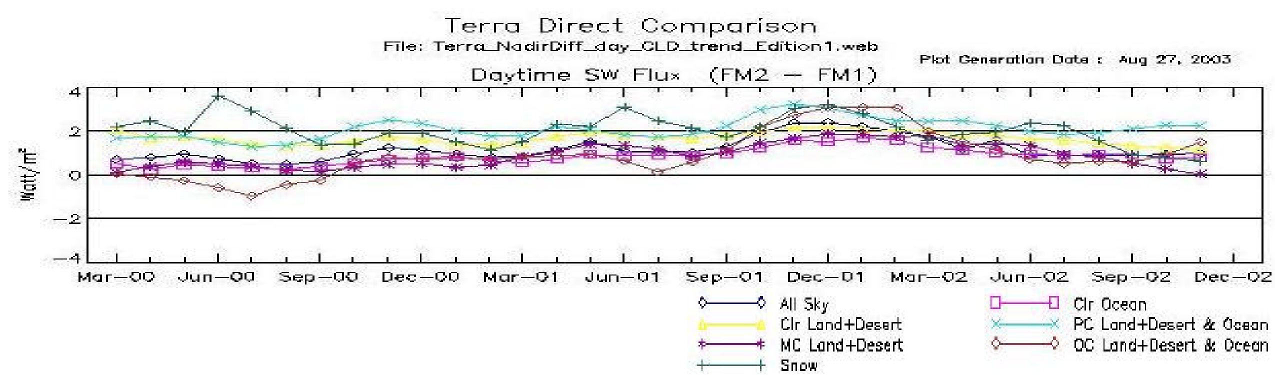


Figure 5: FM2-FM1, Edition 1 data, difference for daytime shortwave flux over mission life for all sky conditions and various cloud and surface types.

A horizontal trend line indicates the sensors of the two instruments are stable with respect to each other. However, the two sensors could be drifting at the same rate and the direct comparison would not indicate a drift since equal trending between the two sensors subtract out. Comparisons between these trending plots indicate that the drift is in the shortwave region of the measurements. The nighttime longwave flux does not indicate any significant change between the two instruments over mission life. However, the daytime longwave flux shows a continuous drift in average values between the two instruments over time. This is more pronounced in the bright scene averages where the difference between the two instruments is greater in magnitude. The daytime shortwave fluxes show little drift in average value between the two instruments. The bright scenes show bigger differences, but there does not appear to be significant drifting in the differences of the shortwave sensors between the two instruments.

2.2.2 Direct Comparison – Aqua, Edition 1 Data Products

The analogous comparisons of the shortwave and longwave fluxes were made for the CERES instruments on Aqua. The daytime and nighttime longwave fluxes and the shortwave flux direct comparisons are shown in figures 6 – 8. Each of these comparisons indicated that the FM3 and FM4 instruments are not drifting in time relative to each other.

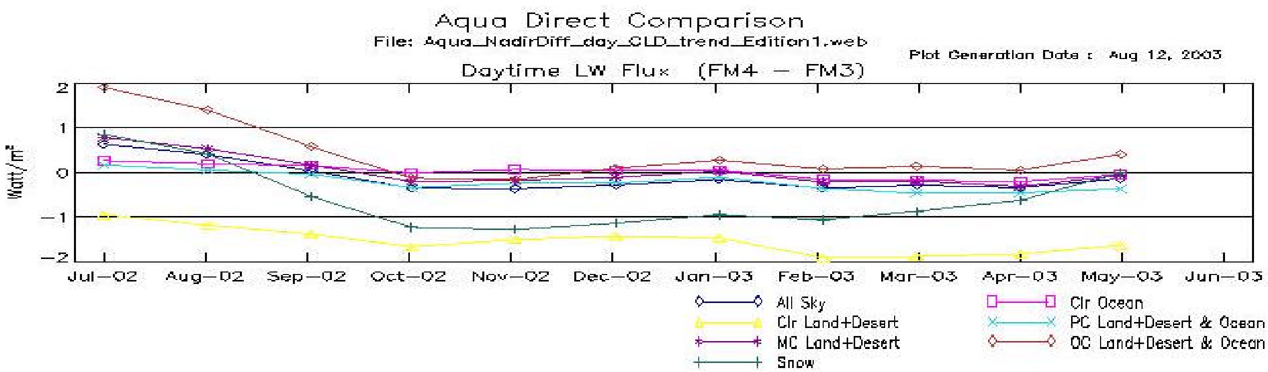


Figure 6: FM4-FM3, Edition 1 data, difference for daytime longwave flux over mission life for all sky conditions and various cloud and surface types.

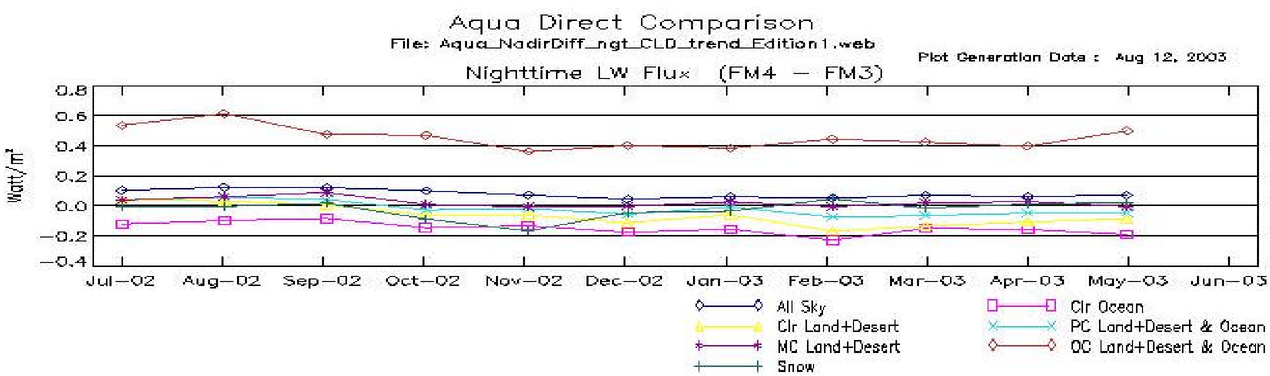


Figure 7: FM4-FM3, Edition 1 data, difference for nighttime longwave flux over mission life for all sky conditions and various cloud and surface types.

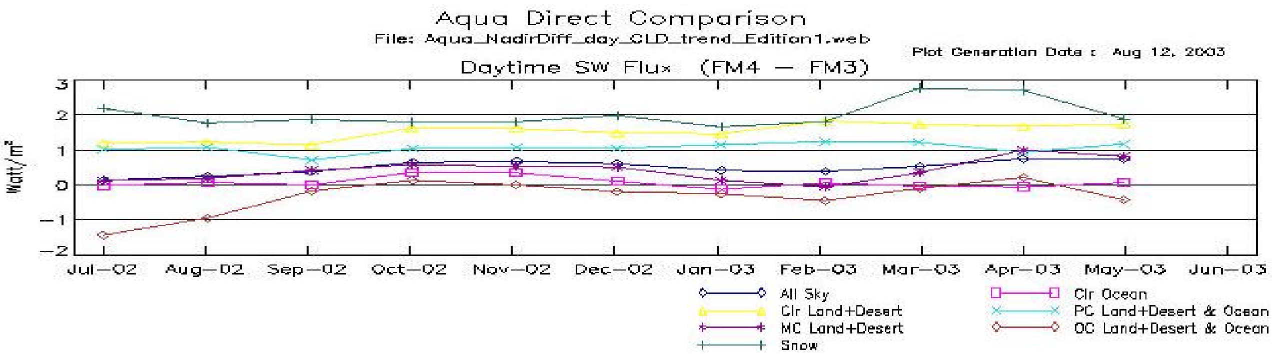


Figure 8: FM4-FM3, Edition 1 data, difference for daytime shortwave flux over mission life for all sky conditions and various cloud and surface types.

2.3 On-Board Calibrations

Gain coefficients are used to convert CERES measurements from electronic count values to radiance units. These coefficients are determined during ground calibrations of the instruments.[5] Once in flight, on-board calibrations are performed weekly to reassess the gain.

2.3.1 On-Board Calibrations - Terra

Figure 9 shows the history of the percent deviation from the ground derived gain coefficients determined from on-orbit calibrations for the three sensors on both instruments. Over mission life, the gains of the total channel sensors for both CERES instruments have increased while the window and shortwave sensor gains have remained somewhat constant although the window sensors have a lower signal to noise ratio.

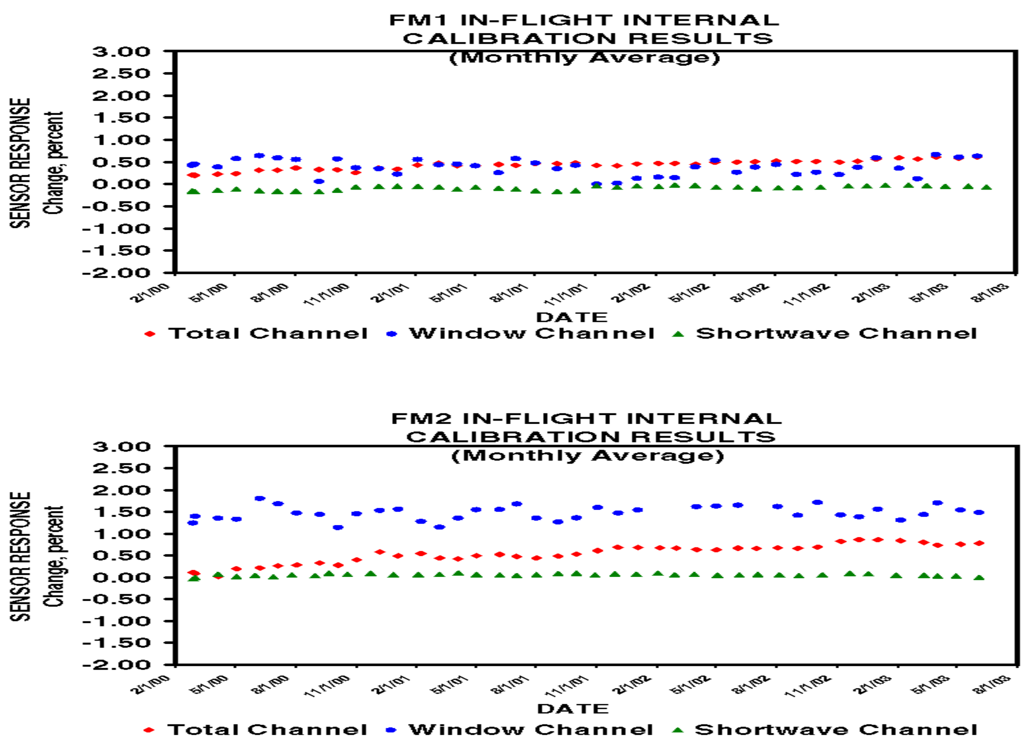
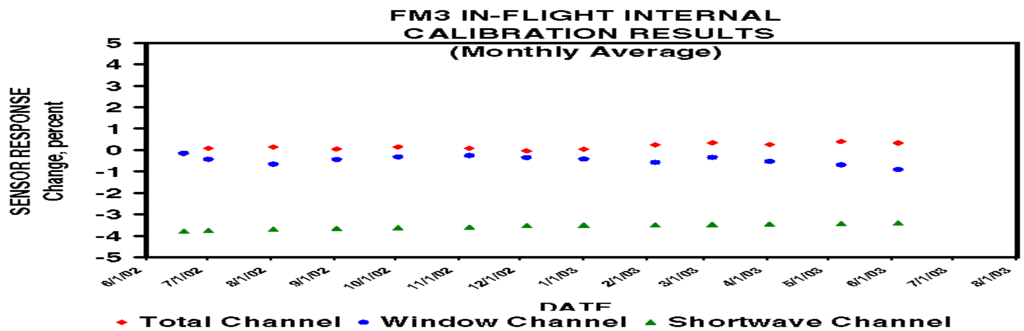


Figure 9: Percent deviation from ground derived gains during on-orbit calibrations for all three sensors of both Terra instruments.

2.3.2 On-Board Calibrations - Aqua

The analogous calibrations for the CERES instruments on Aqua are shown in figure 10. The in-flight calibrations indicate slight drifting in the shortwave sensors of both instruments on the Aqua platform.



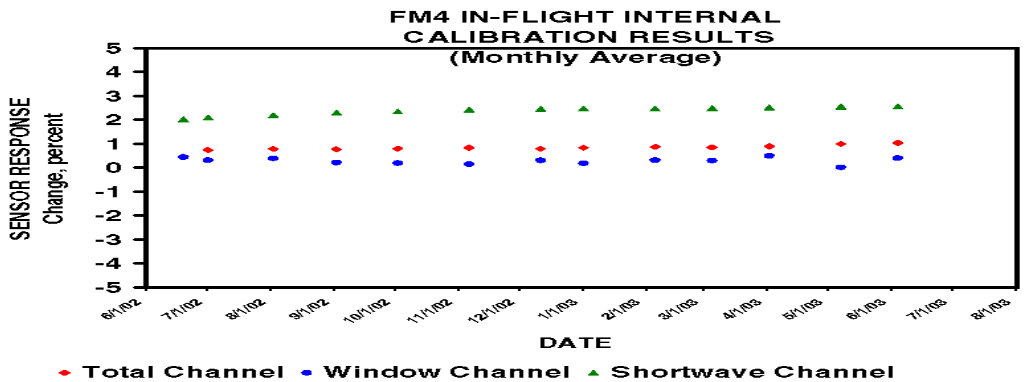


Figure 10: Percent deviation from ground derived gains during on-orbit calibrations for all three sensors of both Aqua instruments.

3. DISCUSSION

3.1 Terra

The three-channel inter-comparison indicates that the ratio of the shortwave portion of the total channel sensor to the shortwave channel sensor is increasing with time (figure 2). This drift is more pronounced in the FM2 instrument and initiates at the beginning of the mission. The drift in the FM1 instrument is less and appears to initiate after March 2001. The direct comparison shows that the average difference of coincident daytime longwave nadir measurements between the two instruments is increasing in time, figure 3. Trending plots do not show a drift in nighttime longwave measurements, figure 4. The window channel sensor is stable in time during both daytime and nighttime. Internal calibrations do not show drift in shortwave channels. Thus, the shortwave portion of the total channel sensor may be too responsive causing the total channel to read high and this mis-reading is increasing with mission time. The daytime unfiltered longwave radiance and flux are derived in part by subtracting the shortwave sensor value from the total channel sensor value. If the total channel errs falsely high, the resulting longwave value will be falsely high for daytime when shortwave values are nonzero. When shortwave is zero during nighttime, the drift is not detected by these analyses.

Mean longwave radiances over the tropical ocean remain very stable over time with a mean variation of about 0.7 percent over a 5-year period. This has been shown by measurements taken by the Earth Radiation Budget Satellite (ERBS) instrument.[6] Thomas[7] applied this technique to the CERES instruments on Terra and found that the daytime minus nighttime differences between monthly averaged longwave unfiltered radiances has increased about 0.25 percent from March 2000 to December 2001 for the FM1 instrument. The drift in the FM2 instrument was about 1 percent. This is consistent with the findings here and indicates drifting of CERES instruments' measurements is occurring in the shortwave region of the total channels. Also, it is consistent that FM2 has a larger drift.

3.2 Aqua

The three-channel inter-comparison, figure 2, indicates a drift in the either the shortwave channel or the shortwave portion of the total channel. The direct comparisons are do not indicate significant drifting. The in-flight internal calibrations indicate small drifting in the shortwave sensors of both instruments, figure 10.

4. DRIFT CORRECTION

4.1 Correcting drift using ground software

The drifting of the sensors' measurements on the CERES instruments has been corrected using ground software. By reducing the gain in the total channel sensor with time, it is hoped to reduce and thus, correct the total channel sensor measurements. A numerical scheme was devised to reprocess raw CERES data from beginning of the mission with gain coefficients linearly adjusted with time over mission life. In addition, the spectral response functions were also incorporated into the scheme to spectrally filter the shortwave portion of the total channel sensor. As with the gain coefficient adjustment, the spectral response function was made to linearly vary with time over mission life.

4.1.1 Drift Correction – Terra, Edition 2 Data Products

FM1, FM2 level-0 data was reprocessed starting with March 2000 to December 2002 with linearly varying gains and spectral response functions. Although the software was written to apply time-varying gain and spectral response functions to all three sensors, only the total channel for both instruments was applied time-varying gain coefficients, figure 11. Initial radiometric gain values for March 2000 were adjusted for ground-to-flight shifts detected by the internal calibrations. Time-varying spectral response functions were applied to the FM1 instrument after February 2001. The FM2 instrument has had time varying spectral correction to the total channel sensor since the beginning of the mission, figure 12.

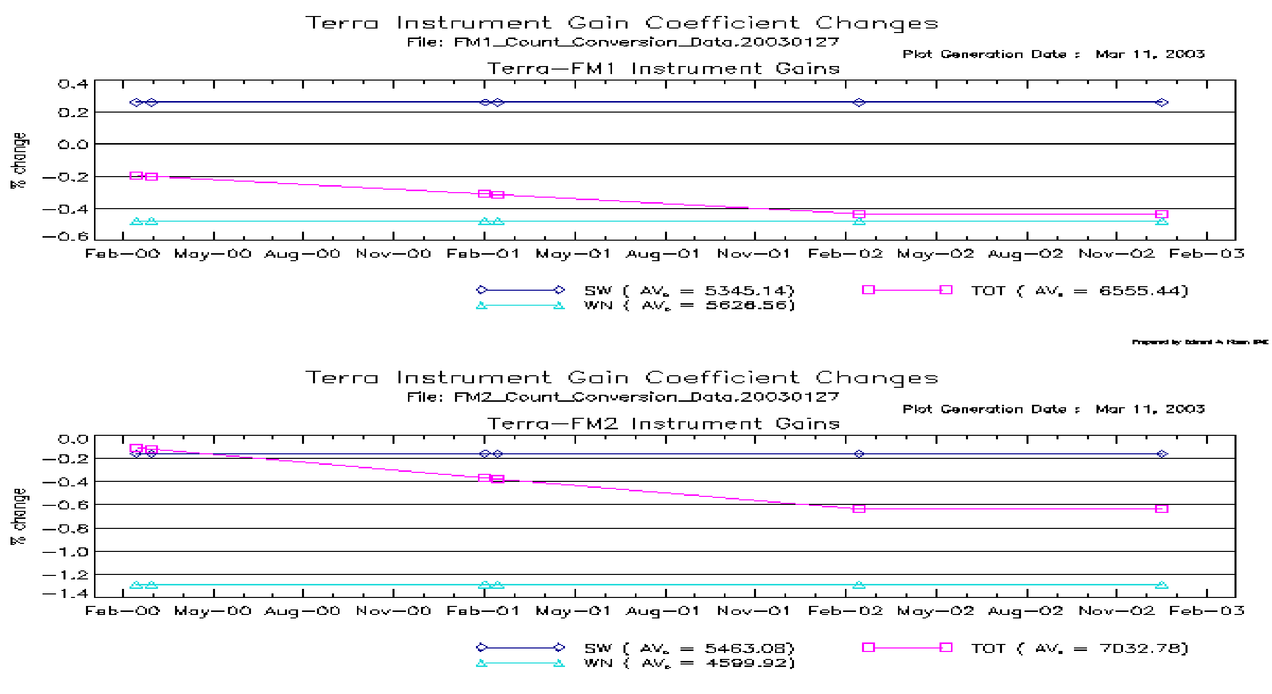


Figure 11: Percent deviation from initial on-orbit derived gains for all three sensors of both CERES instruments on Terra.

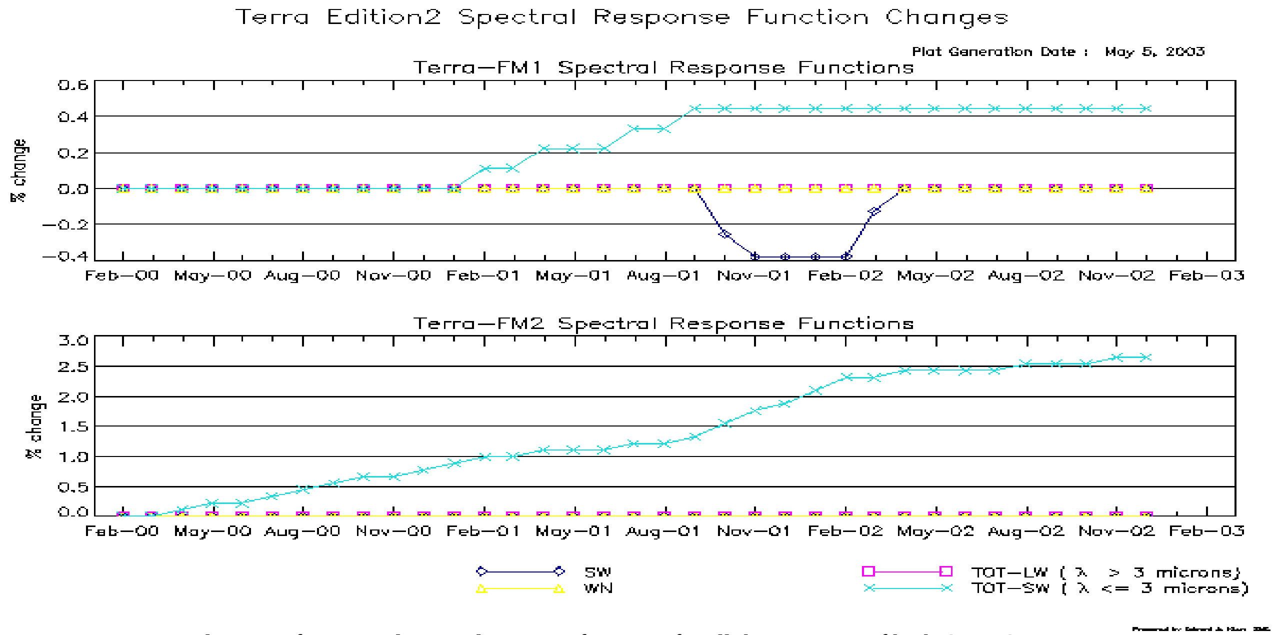


Figure 12: Percent deviation from initial spectral response functions for all three sensors of both CERES instruments on Terra.

4.1.2 Drift Correction – Aqua, Edition 2 Data Products

Aqua drift correction will occur in the Edition 2 data products that will be released in spring 2004.

4.2 Three-Channel Inter-comparison Using Deep Convective Clouds, Edition 2 Data Products

The improvement of the three-channel inter-comparison using unfiltered radiances (figure 13) is pronounced. The drift in ratio of delta longwave to shortwave in FM2 is removed. No change in spectral response functions was applied to the FM1 instrument for the year 2000, so the improvement here is due solely to time-varying gain coefficients in the total channel sensor.

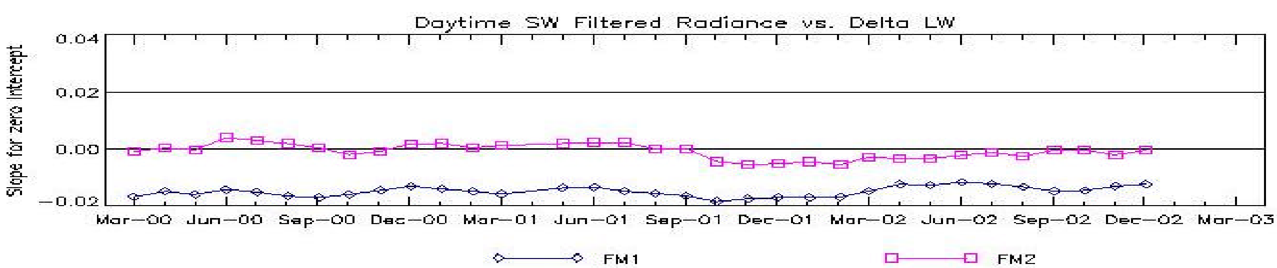


Figure 13: Trending of the ratio of the delta longwave to the measured shortwave channel for the Terra instruments using the three-channel inter-comparison using Edition 2 data products that implement corrections to gains and spectral response functions.

4.3 Direct Comparison, Edition 2 Data Products

When directly comparing coincident nadir measurements, the daytime longwave differences, figure 14, show the most improvement with implementing the time-varying drifts and spectral corrections. These results can be compared with the Edition 1 data shown in figure 3.

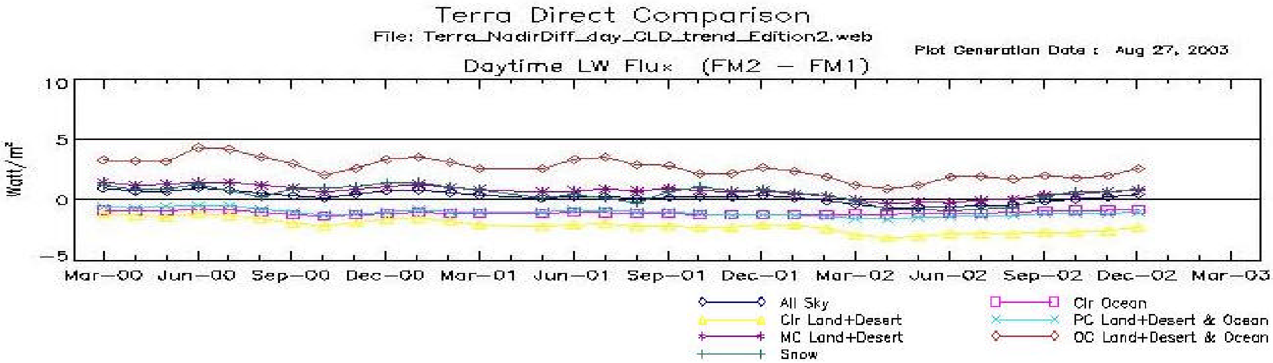


Figure 14: FM2-FM1, Edition 2 data, difference for daytime longwave flux over mission life for all sky conditions, various clear scenes, and bright scenes after corrections to gain and spectral response functions.

The nighttime longwave differences, figure 15, are about the same as previous, figure 4. The shortwave flux shown in figure 16, is not much improved over the previous results, figure 5. These indicate that corrections to the total channel sensor did not have an adverse effect on the values dependent upon the total sensor measurement (longwave is derived by subtracting shortwave from total).

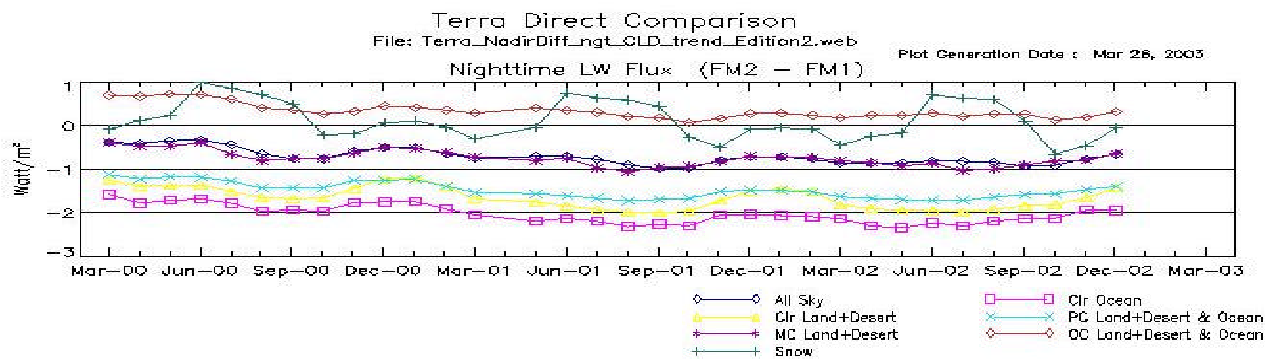


Figure 15: FM2-FM1, Edition 2 data, difference for nighttime longwave flux over mission life for all sky conditions and various clear scenes after corrections to gain and spectral response functions.

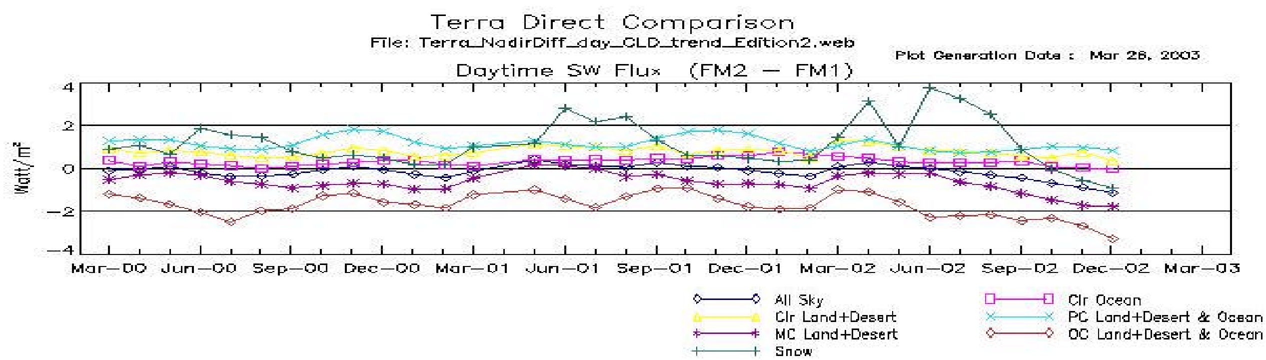


Figure 16: FM2-FM1, Edition 2 data, difference for daytime shortwave flux over mission life for all sky conditions, various clear scenes, and bright scenes after corrections to gain and spectral response functions.

5. CONCLUSIONS

Analyses have been developed using ground-based software to aid in monitoring the stability of the CERES instruments' radiance measurements in space. The three-channel inter-comparison is used to detect inconsistencies between the three sensors. The direct comparison can detect inconsistencies between coincident measurements between two instruments on the same platform. Implementing these analyses on the CERES instruments on the Terra satellite has shown that the ratio of the shortwave portion of the total channel sensor to the shortwave sensor is increasing with time, especially in the FM2 instrument. The direct comparison showed that the differences between instruments mainly in daytime longwave values are increasing with time. It is believed that the shortwave portion of the total channel sensor is reading high for the FM2 instrument. Also, the FM1 instrument may be reading low in its shortwave sensor. Applying time-varying gains and spectral corrections has removed this drift and the Edition 2 (BDS, ES-8) data products. Results from these analyses applied to the CERES instruments on the Aqua satellite indicate that the radiometric measurements are drifting in time. These drifts will be corrected in the Aqua BDS and ES-8 Edition 2 data products scheduled to be released in spring 2004. Additional work needs to be done to isolate the causes of drift in the CERES detectors and more exact methods of removing the drift using ground software.

ACKOWLEDGMENTS

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REFERENCES

1. B. A. Wielicki, B. R. Barkstrom, E. F. Harrison, R. B. Lee III, G. L. Smith, and J. E. Cooper, “Clouds and the Earth’s Radiant Energy System (CERES): An Earth Observing Experiment”, *Bulletin of American Meteorological Society*, **77**, pp. 853-868, 1996.
2. K. J. Priestley, B. R. Barkstrom, R. B. Lee III, R. N. Green, S. Thomas, R. S. Wilson, P. L. Spence, J. Paden, D. K. Pandey, A. Al-Hajjah, “Postlaunch Radiometric Validation of the Clouds and the Earth’s Radiant Energy System (CERES) Proto-Flight Model on the Tropical Rainfall Measuring Mission (TRMM) Spacecraft Through 1999”, *Journal of Applied Meteorology*, **39**, No. 12, pp. 2249-2258, December 2000.
3. N. G. Loeb, K. J. Priestley, D. P. Kratz, E. B. Geier, R. N. Green, B. A. Wielicki, P. O. Hinton, S. K. Noland, “Determination of Unfiltered Radiances from the Clouds and the Earth’s Radiant Energy System (CERES) Instrument”, *Journal of Applied Meteorology*, 40, 822-835, 2001.
4. P. L. Spence, K. J. Priestley, S. Thomas, “In-flight stability analyses applied to the Clouds and the Earth’s Radiant Energy System scanning thermistor bolometer instruments on the Terra satellite”, Proceedings of SPIE, Earth Observing Systems VII, Seattle, WA, 7-10 July, 2002.
5. R. B. Lee, and Coauthors, “Prelaunch Calibrations of the Clouds and the Earth’s Radiant Energy System (CERES) Tropical Rainfall Measuring Mission and the Earth Observing System Morning (EOS-AM1) spacecraft thermistor bolometer sensors. *IEEE Transactions Geoscience Remote Sensing*, **36**, 1173-1185, 1998.
6. R. N. Green, L. M. Avis, “Validation of ERBS scanner radiances”, *Journal of Atmospheric and Oceanic Technology*, **13**, 851-862, 1996.
7. Thomas S., K. J. Priestley, P. L. Spence, E. A. Kizer, D. L. Walikainen, "On-orbit stability results of CERES instruments aboard EOS TERRA and AQUA spacecrafts using tropical ocean measurements", Proc. of IGARSS'03, Toulouse, France, July 2003.